CONSTRUCTION OF A THETA-PINCH FOR THE GENERATION OF SHOCK WAVES IN A NITROGEN PLASMA

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THESIS

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ABSTRACT

A Theta-Pinch device was constructed for the production of shock waves in a nitrogen plasma. The device consisted of six 7μF capacitors in parallel, and a one turn coil through which the capacitors were discharged. The rise time of the current in the coil is one microsecond, and the stored energy in the capacitors is 13 kJ at 25 kV. The large perturbation of the plasma is expected to produce large amplitude Alfvén waves which would propagate up the plasma column.

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ACKNOWLEDGEMENT

During all phases of this project, a great many people contributed their ideas, time, and effort. Principal thanks go to Professor Alfred Cooper for his overall assistance, encouragement, and guidance, Hal Herreman for his help and ideas in the laboratory, Mike O'Day for his contribution to the design and assembly of the apparatus, and Bob Smith for his assistance during assembly of the device.

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I. INTRODUCTION

This work is the continuation of the study of the characteristics of a fully ionized nitrogen plasma. This report concerns the design, construction, and testing of a fast theta-pinch bank. The purpose of the bank is to generate shock waves in a steady-state plasma. The main interest lies in studying the properties of the shock waves as they travel down the plasma column. The reason for studying these shock waves is that similar shocks are produced in upper atmosphere thermonuclear explosions. Shock waves are also produced by the earth's passage through the solar wind. There are many other phenomena in astrophysics which can be described by a shock wave traveling through a plasma.

A. BACKGROUND

The plasma facility at the Naval Postgraduate School consists of a hollow-cathode plasma source placed at one end of a ten-foot pyrex column set on the axis of a solenoid. The machine is capable of producing a steady-state magnetic confinement field up to 10,000 gauss and homogeneous to within 2.5% along the axis. Figure 1 is a sketch of the plasma machine which shows the relative location of the principal parts of the machine, including the position of the pinch coil. The machine produces a steady-state plasma with a density in the order of 10^{13} cm^{-3}. The electron temperature ranges from 3.5 to 8.0 ev. and the maximum ion temperature is 5×10^3 °K. For nitrogen the collision times are: [1]

$$\tau_{ee} = .148 \times 10^{-6} \text{ sec}$$

$$\tau_{ii} = .754 \times 10^{-6} \text{ sec}$$

$$\tau_{ei} = 260.8 \times 10^{-6} \text{ sec}$$

These collision times are for a plasma with the following parameters:

$$T_e = 5 \times 10^4 \text{ °K}$$

$$T_i = 5 \times 10^3 \text{ °K}$$

$$n_e = n_i = 2 \times 10^{18} \text{ m}^{-3}$$

$$\ln \Lambda = 10$$

B. THEORY

The shock wave is produced by a six-inch long pinch coil that is wrapped around the plasma. The coil is connected to a fast-discharge capacitor bank. The short rise time to maximum current in the coil causes a large perturbation of short duration on the plasma. This perturbation is expected to cause Alfvén waves to propagate along the plasma column. If the leading edge of the Alfvén wave travels at a slower velocity than the regions behind it, the wavefron steepens and forms a shock wave. This shock wave formation will occur if the magnetic field rise time is short. The mechanical effect of the magnetic field on the plasma is equivalent to a hydrostatic pressure transverse to the field lines and a tension along the lines. The system is analogous to an elastic band under tension. The transverse waves, which propagate in the direction of the magnetic field due to the coupling of the plasma particles with the field lines, are commonly called Alfvén waves. The Alfvén waves travel with the characteristic velocity

$$V_A = \frac{B_o}{\mu_o \rho_o} \quad [2] \; .$$

If B_o is assumed to be 3000 gauss and ρ_o $10^{13} \times M_N$, then $V_A = 5.6\text{x}10^7$ cm/sec.

Alfvén waves are produced by perturbing the magnetic field. This can be accomplished by twisting the field lines, by a displacement of the ionized mass, or by compressing the magnetic field lines as is done in the theta-pinch. The current (j_ϕ) flows in the coil. This creates an axial magnetic field B_Z. As a first approximation the plasma is assumed to have infinite conductivity which means that B_Z cannot penetrate the plasma. Therefore a current sheath is induced in the plasma surface which is equal in magnitude but opposite in direction to the current in the coil. Since the field inside is much smaller than the field outside the sheath, the sheath behaves like a "magnetic piston" and sweeps up all the charged particles that it encounters. The rate of momentum change of the plasma, balanced against the external magnet pressure, then gives the inward velocity of the sheath as a function of time. This is known as the snowplow model of the pinch discharge.

One of the criteria for a collisionless shock wave is that $\tau_{ii} \geq t_r$ where t_r is the risetime of the current in the theta-pinch. The other criterion is that $t_r \leq \frac{R}{V_A}$ where R is the radius of the coil. $\frac{R}{V_A}$ is $.5 \times 10^{-7}$ sec. From these two criteria the risetime of the current in the theta-pinch must be in the order of .05 - 1.0 microsecond.

In two previous attempts to produce shock waves at the Naval Postgraduate School, Andrews [3] and Beam [1] were unsuccessful in detecting the waves downstream from the coil. This was attributed to the very large damping of these waves in the plasma. The present work attempts to overcome this problem by increasing the magnitude of the perturbation by a factor of 50 over Beam's theta-pinch. Beam charged a .75 μF capacitor to 20 kV whereas the present work has a total of 42 μF charged to 24 kV.

II. THE THETA-PINCH BANK

A. DESCRIPTION

The bank consists of six 7 μF capacitors in parallel. The capacitors are charged to 25 kV with a power supply capable of a maximum current of 50 mA. The capacitors are connected to the one turn coil by means of 8.8 cm inch wide copper strip lines. Each capacitor is discharged by a four-element, pressurized spark gap placed in series with the capacitor and load coil. The six spark gaps are fired in parallel by the master four-element spark gap which is charged to 40 kV. The master gap derives its power from a separate 40 kV power supply. The master gap is triggered by a 12 kV thyratron pulse that is put through a 4:1 pulse transformer.

B. ARRANGEMENT OF THE BANK COMPONENTS

Figure 2 shows the floor layout of the main components of the system. The positioning of the components was dictated by the space available, ease of access to the equipment, and the experimental requirements of the system. The system has a local and remote control panel. The local controls were installed for the convenience of the experimenter during the construction and testing of the system. The remote controls are used by the experimenter when he is using the theta-pinch system for experiments. The capacitors are located approximately four feet from the plasma machine so that there is limited access to the machine from that side.

C. DATA

The following table lists the most important data of the theta-pinch bank:

Parameters of the Theta-Pinch Bank

Charging voltage	25 kV
Capacitance	42 μF
Stored energy	13.1 kJ
Peak current	255 kA
Discharge ringing frequency	172 kHz
Peak flux density	20 kG
Initial risetime of the current	1 μs
Coil length	14.5 cm
Coil diameter	5.5 cm
Inductance of the coil	18 nH
Total inductance of system	64 nH

The charging voltage is measured by placing .5 milliampere ammeter with 100 megaohms series resistance across the terminals of one of the capacitors. The stored energy of the bank is given by the equation:

$$E = \frac{1}{2} CV^2$$

where E = energy in joules

C = capacitance in farads

V = voltage in volts

The peak current was measured by McLaughlin [4] using a magnetic probe that he developed. The discharge ringing was also measured using the magnetic probe. The peak flux density is given by the equation:

$$B = \frac{\mu_o I}{4R^2+\ell^2}$$

where B = flux density in webers/meter

μ_o = $4\pi \times 10^{-7}$ henrys/meter

I = current through solenoid in amperes

ℓ = length of solenoid in meters

R = radius of solenoid in meters

The initial rise time of the current is defined as the time it takes for the current to increase from 10% to 90% of its maximum value. This is approximately one-sixth of the period of the ringing frequency. The inductance of the coil is calculated from the equation:

$$L = dF$$

where d = diameter of the coil in centimeters

F = constant that depends on the ratio of length to diameter and is given by Terman [5]

The total inductance of the system is given by the equation:

$$L = \frac{1}{4\pi^2 f^2 c}$$

where L = inductance in henrys

f = frequency in hertz

c = capacitance in farads

III. DESIGN AND CONSTRUCTION OF THE THETA-PINCH

A. CAPACITORS, STRIP LINES, AND PINCH COIL

Figure 3 is a picture of the capacitor bank which shows how the capacitors are arranged and where the pressurized, four-element spark gaps are located. The capacitors are low inductance 7 μF Axel capacitors rated at 25 kV. They are stacked on a steel rack in two columns with three capacitors in each column. The steel rack and the capacitor cases are at ground potential. This arrangement of the capacitors was chosen to conserve floor space and for ease in assembly of the bank. Aluminum sheets of 150 mil thickness were bolted to three sides of the capacitor rack. The purpose of the aluminum sheets is to protect laboratory personnel from possible explosions due to the failure of one of the capacitors or spark gap boxes. The sheets also act as a ground shield to protect personnel from possible arcing.

The strip lines are parallel copper strips, 8.8 cm wide and .16 cm thick, separated by 10 mil mylar sheets. The strip lines have an inductance of 3.6 nH/m. The inductance of the strip lines is given by the equation: [6]

$$L = 4\pi \times 10^{-7} \frac{t}{W}$$

where L = inductance in henries/meter

t = separation between the parallel strips

W = width of the strips

This is equivalent to placing approximately eighteen RG 19/17 coax cables in parallel. RG 19/17 cable has the lowest inductance of any commercially available cable. In this experiment all inductances must

be minimized so that the risetime is as short as possible. The risetime must be in the order of 1 microsecond so that shock waves are produced in plasma. Figure 4 shows how the six strip lines join to one strip line which enters the plasma machine and connects to the pinch coil. The main problem encountered in the assembly of the strip lines was holding together the pairs of parallel strips and bending the lines into position. Another consideration in constructing the lines is that large amplitude magnetic pressures of short duration are produced by current flowing in opposite directions through each pair of strips. For this bank a peak pressure of 19 atmospheres is given by the equation: [6]

$$P = 2\pi \frac{I^2}{W^2} 10^{-12}$$

where P = pressure in atmospheres

I = current in amperes

W = width in meters

To overcome the above problems, micarta clamps were used to hold the parallel strips together. The interval between clamps was one foot or less. Micarta was used because it has good electrical insulation and strength properties.

A problem that showed up during the testing of the bank was the finite resistance of the joints connecting sections of the strip lines. The joints were made by turning up 2 cm at the ends of the strip line. A 1/16 inch piece of copper was soldered to the upturned end and machined smooth. The ends were drilled and bolted together. For small currents this type of joint looks like a dead short, but for large currents on the order of 10^5 amps, the joint has a finite resistance which represents

an energy loss. The explanation for this phenomenon is that there is electrical contact at a finite number of points along the joint. The area of contact can be increased by coating the joint with a special grease. This grease contains silver to enhance its electrical conductance properties.

Figure 5 is a schematic of the theta-pinch coil. The coil is 5.5 cm in diameter and made of 1/8 inch copper. The coil was made small to conserve magnetic field. The clearance between the galss tube and the coil is one hundredth of an inch.

B. SPARK GAPS

The four-element, pressurized spark gaps are based on the spark gaps developed by the Institute for Plasma Physics at Garching, Germany [7,8,9]. Gross [10] gives a good survey account of the different types of switches that can be used for bank switching.

> There are two distinct kinds of low-inductance switches: those known as spark-gap switches, for which the open condition consists of two electrodes separated by vacuum or some gaseous insulator, e.g., air, argon, SF_6, Freon 12, etc.; and those known as solid dielectric switches, for which the open condition consists of two electrodes separated by a solid dielectric material. Both kinds of switches may be closed either by providing an over-voltage for the given gap or by triggering the gap through initiation of an electric discharge in the insulating media between the electrodes. Either way, a conducting path between the electrodes is established through which flows the large current from the main energy source.
>
> The dielectric switch offers the advantage of having the smallest possible inductance of any switch. It has, however, the disadvantage that each time it is fired, the dielectric is destroyed and must be replaced. If the anticipated frequency of firings is more than one a minute, or even more than one or two switches are employed, the problem of resetting the switch becomes very bothersome. The vacuum spark gap switch can be made with low inductance, but at elevated voltages, the switch acts like an x-ray

tube with all its attendant difficulties. The gaseous spark gap switch has the highest inductance, but it offers the advantage that it requires no resetting after every shot. It can operate at discharge frequencies of many hundreds of shots per second if necessary and it has not x-ray problem. Furthermore, if the dielectric used between the electrodes is one whose dielectric strength is considerably larger than air, like SF_6 or Freon 12, the switch inductance can be reduced to values in the 10-20 nh range. By going to a pressurized gas switch, still lower inductance can be achieved, but the switch becomes a bulky pressure vessel which must be capable of withstanding the discharge internal blast wave.

It should be noted that if the low inductance requirement can be relaxed, if the bank voltage is 20 kv or less, and if rise times greater than 1 μs can be tolerated, the best switch is the cold mercury cathode ignitron. Over the years, commercial ignitrons have been improved to the point where they are inexpensive, quiet, easy to fire, and reliable. General Electric and National Electronics manufacture a special line of ignitrons designed for capacitor discharge service. They can be operated at up to 20 kv peak anode voltage and will carry up to 100 ka for 20 μs. More current can be carried if the pulse duration is shorter than 20 μs. An ignitron is essentially a uni-directional device (it acts like a rectifier) but if the current oscillation period is shorter than the de-ionization time within the ignitron, it will conduct in both directions. [10]

The spark gaps were modeled after those developed at Garching because the electrical properties were designed for fast bank application. The switches could be fabricated with the resources available and the Garching group had written extensive reports on the development and evaluation of their switches. The switches are pressurized to reduce the gap size, which in turn decreases the switch inductance. The pressurization of the switch makes possible easy adjustment of the stand-off voltage. The jitter time and the time for break down of the gas is decreased by using a four-element spark gap. The trigger voltage is independent of the stand-off voltage of the main gap. Figure 6 shows the geometry of the gaps and a circuit diagram for the switch. Figure 7

is a schematic drawing of the units. The elements are cylindrical in shape instead of hemispherical so that the cross-sectional area of the gap through which the current flows is increased and therefore the current capability of the switch is increased.

> The initial electrode is taken out of the area of erosion by mounting it inside the hollow trigger electrode, and receives the trigger pulse, which causes breakdown between the pin and the trigger electrode with no greater jitter and delay, than the formative and statistical time lag of a very high over-volted gap. (dc-breakdown in the range of 4 - 10 kV, applied pulse 40 - 70 kV) The irradiation coming from this initial arc is led to both gaps by holes in the trigger rod, assisting their breakdown. The potential of the trigger rod now becomes that of the trigger pulse by means of the auxiliary arc, producing a strongly heterogeneous field between the main electrodes. The breakdown is no longer a pure overvolted Townsend mechanism, but being assisted by irradiation and high field strength acceleration just on those spots, where electrons are liberated. High field strength exists in the surrounding of the trigger rod holes and adjacent to the opposite surface of the main electrodes. At both spots irradiation is most intense. By choice of a trigger pulse polarity with opposite sign to bank charging voltage, electrons are in areas of large positive voltage gradient at both bank charging polarities. Because of the applied trigger pulse circuit, pulse polarity is opposite to the trigger charging voltage. Selection of the geometrical position and the static potential of the trigger rod, the amplitude of the pulse, and even the intensity of radiation influences the overvoltage of the working gaps. [7]

The elements of the main gap are made of aluminum which has a low work function. The trigger element shell is stainless steel with a tungsten pin along the center of the element. Stainless steel and tungsten are used because they resist erosion caused by the electrical arcs. The pin is surrounded by a teflon sleeve for support and electrical insulation. The strip lines and supports for main gap elements are made of copper, which is an excellent electrical conductor. The pressure vessel is made of one-inch thick plexiglass and is capable of holding a

test pressure of 100 psi. For safety, the switch should not be operated above 80 psi. The plexiglass was bonded to itself using ethylene dichloride, and epoxy was used to bond the plexiglass to the metal parts. Building the pressure vessel of plexiglass represents the major deviation from the Garching design and the major problem in construction of the spark gaps. The Garching group built their spark boxes by vacuum molding epoxy and carefully curing it. The Naval Postgraduate School lacks the resources for vacuum molding. Much experimentation was needed to find an electrical insulating material which possessed the necessary mechanical strength to withstand a test pressure of 100 psi. The gas used in the box is nitrogen that has passed through a cold trap of frozen alcohol to remove possible traces of water and oil vapor. There were no electrical problems encountered in development of the switches. The Garching reports recommend purging one half the volume of the box after each firing of the spark gap. It was found from experience that if the boxes were not purged, a misfire could occur after a few firings of the gap. Figure 8 is a picture of one of the spark gap switches taken after installation into the system.

C. TRIGGER SYSTEM

The trigger system was adopted from the system used at Garching. Figure 9 is the circuit diagram for the trigger system. The system consists of a 12 kV thyratron pulse generator of 10 nanosecond duration, a 4:1 pulse transformer, a master spark gap, and one spark gap for each capacitor. The cables connecting the master spark gap to the six other spark gaps are each 14 meters of RG8/U coaxial cable. The trigger system has been completely reliable. No misfiring of any of the six spark switches in parallel has been observed.

D. POWER SUPPLIES AND CONTROL SYSTEM

Figures 10a and 10b show the control circuit for the theta-pinch bank. The control circuit performs four functions: 1) Charging the capacitors and master spark gap, 2) dumping the capacitors and master spark gap, 3) discharging the capacitors through the pinch coil, and 4) purging the nitrogen gas in the pressure boxes. Figure 9 shows the vacuum switches K8A, K9A, and K10A and K11A through which the control system controls the bank. K8A and K10A are shorting switches which are normally closed and prevent the capacitors from collecting a lethal charge. K9A and K11A are normally open and are used to charge the capacitors. The 25 KV circuit charges the capacitor bank up to 25 KV and the 50 KV circuit normally charges the master spark gap to 40 KV. When the 50 KV charge button is pushed, the K8A switch opens, the K9A closes, and charging begins. When the 50 KV dump button is pushed, the K9A switch opens, then the K8A switch closes, and the circuit is shorted to ground. These sequences of switch activation are important so that a direct short to ground from the power supply does not occur at any time. The 25 KV circuit works in a similar manner and the control circuit for it is the same as for the 50 KV circuit. When the fire button is pushed, the trigger generator sends out a pulse that causes the bank to discharge through the coil, then the K9A and K11A switches open, and then the K8A and K10A switches close. There is a light on the control panel for each circuit that indicates when the circuit is shorted, and another light that indicates when each circuit is charging. The 25 KV circuit has another light that is activated by a meter relay when the capacitors are charged to the desired voltage. When K11A is closed, two red lights flash over the capacitor bank. The

portable fire button enables the experimenter to discharge the bank while observing the bank from any desired position. For safety the bank automatically assumes a dump status immediately after the bank fires. It will assume the dump status even if there is a misfire or a power failure to the control circuit. The only possible failure that would leave all or part of the system in a charged state is if K8A and/or K10A jammed in the open position. To avoid this problem, a mechanical dump should be added to the system.

IV. SUMMARY OF PRESENT STATUS OF THETA-PINCH BANK

At the present the capacitors have been charged up to 13 kV and discharged through the coil. The maximum current through the coil has been recorded as 132 kA. Two problems have occured. During the second discharge at 13 kV, mechanical vibrations due to magnetic pressures generated during the discharge caused the glass tube surrounded by the coil to shatter. These mechanical vibrations have not yet been analyzed. During the fourth and succeeding discharges there was arcing around the mylar inside of the coil.

Four things must be done before the theta-pinch experiment can proceed: 1) An attempt should be made to analyze the origin of the mechanical vibrations. 2) The pinch coil must be rigidly reinforced to prevent mechanical vibrations from shattering the glass tube. 3) The mylar insulation inside the coil should be extended. 4) The joints between sections of the strip lines should be coated with conducting grease.

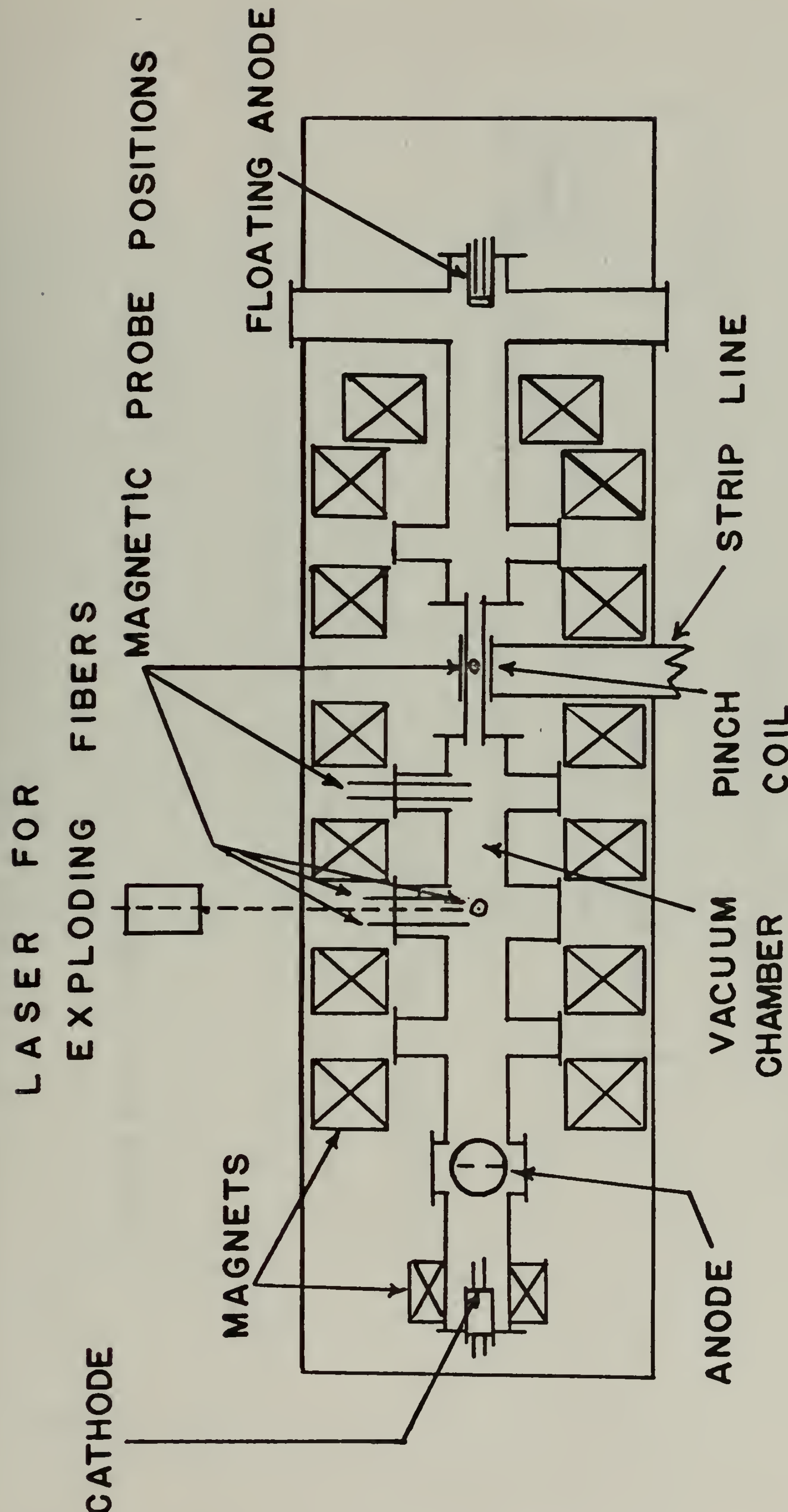


FIGURE 1.
PLANE TOP VIEW OF PLASMA MACHINE

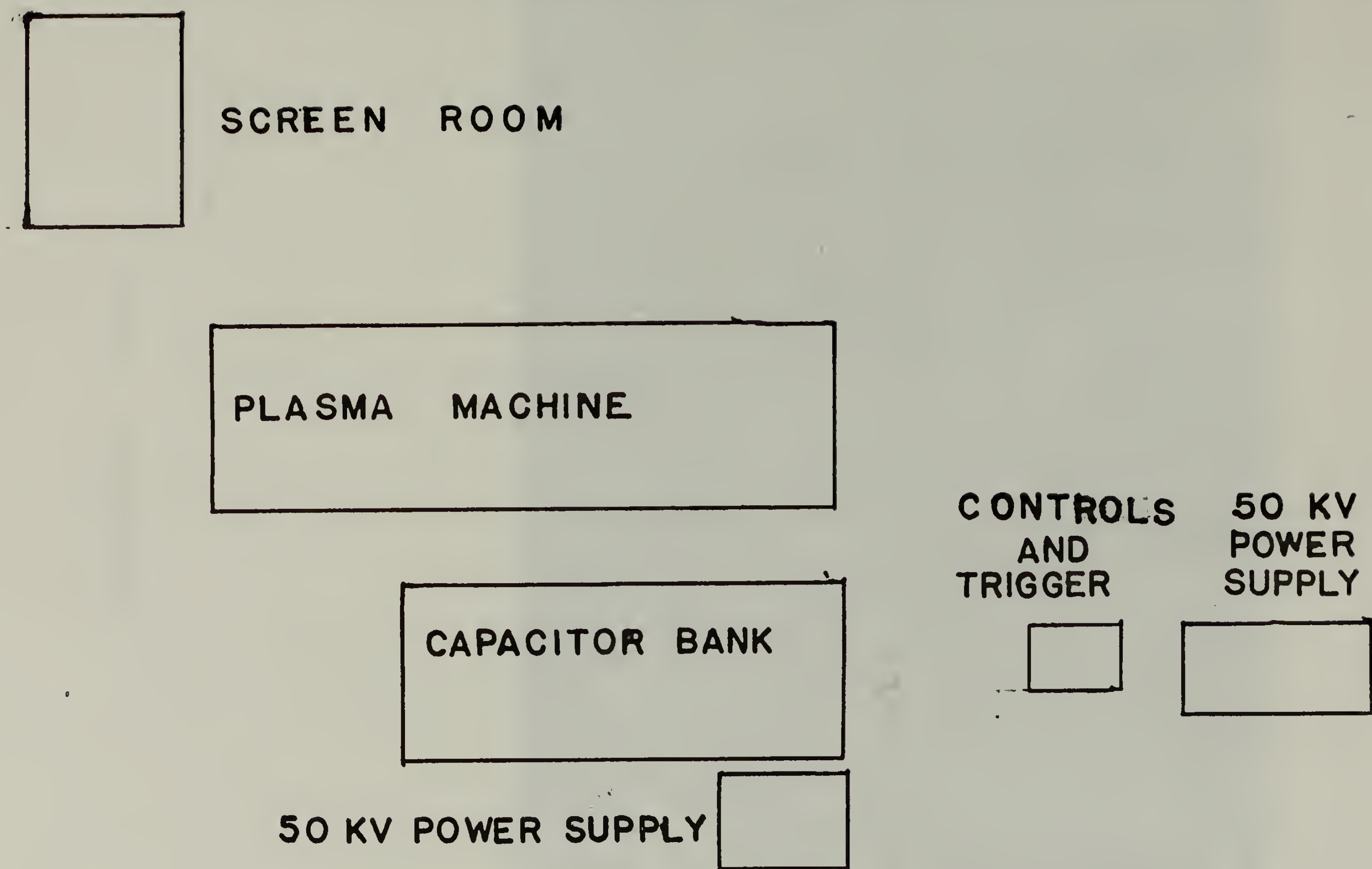


FIGURE 2 FLOOR LAYOUT OF SYSTEM

FIGURE 3. CAPACITOR BANK

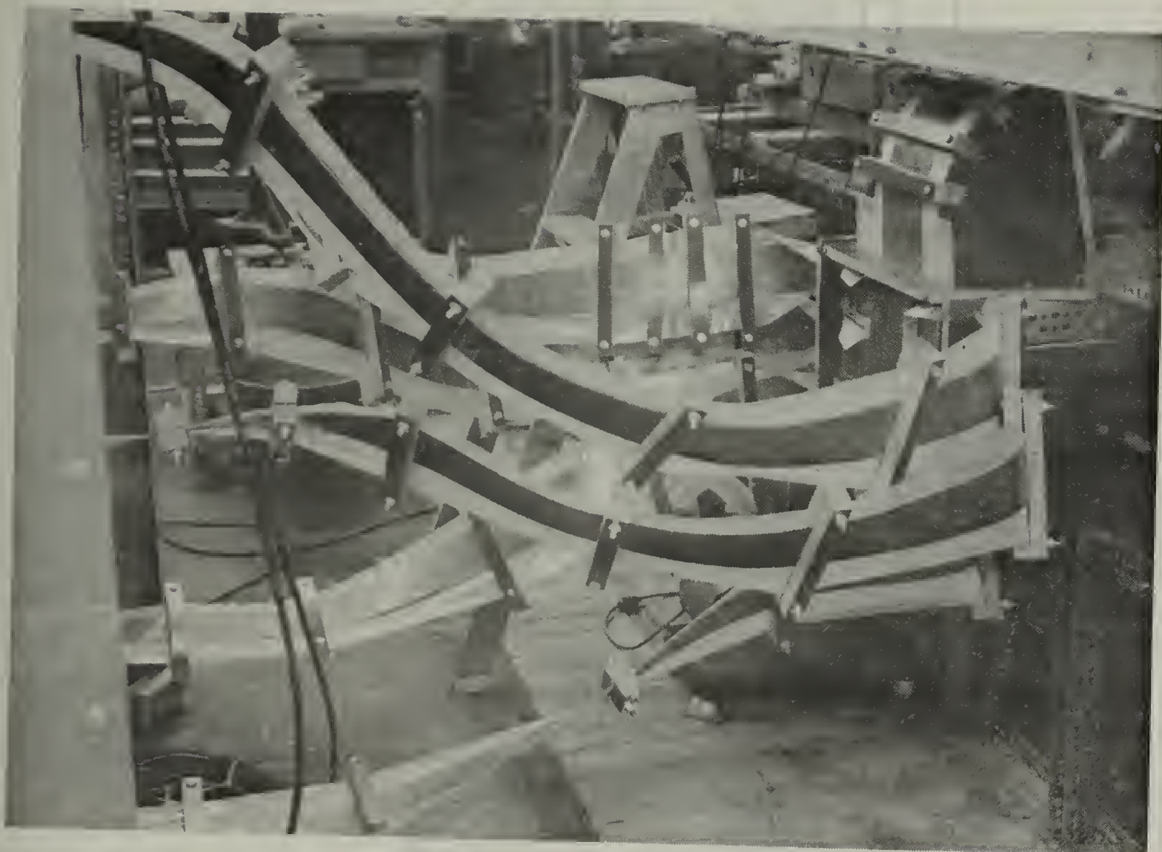


FIGURE 4. STRIP LINE BANK CONNECTION

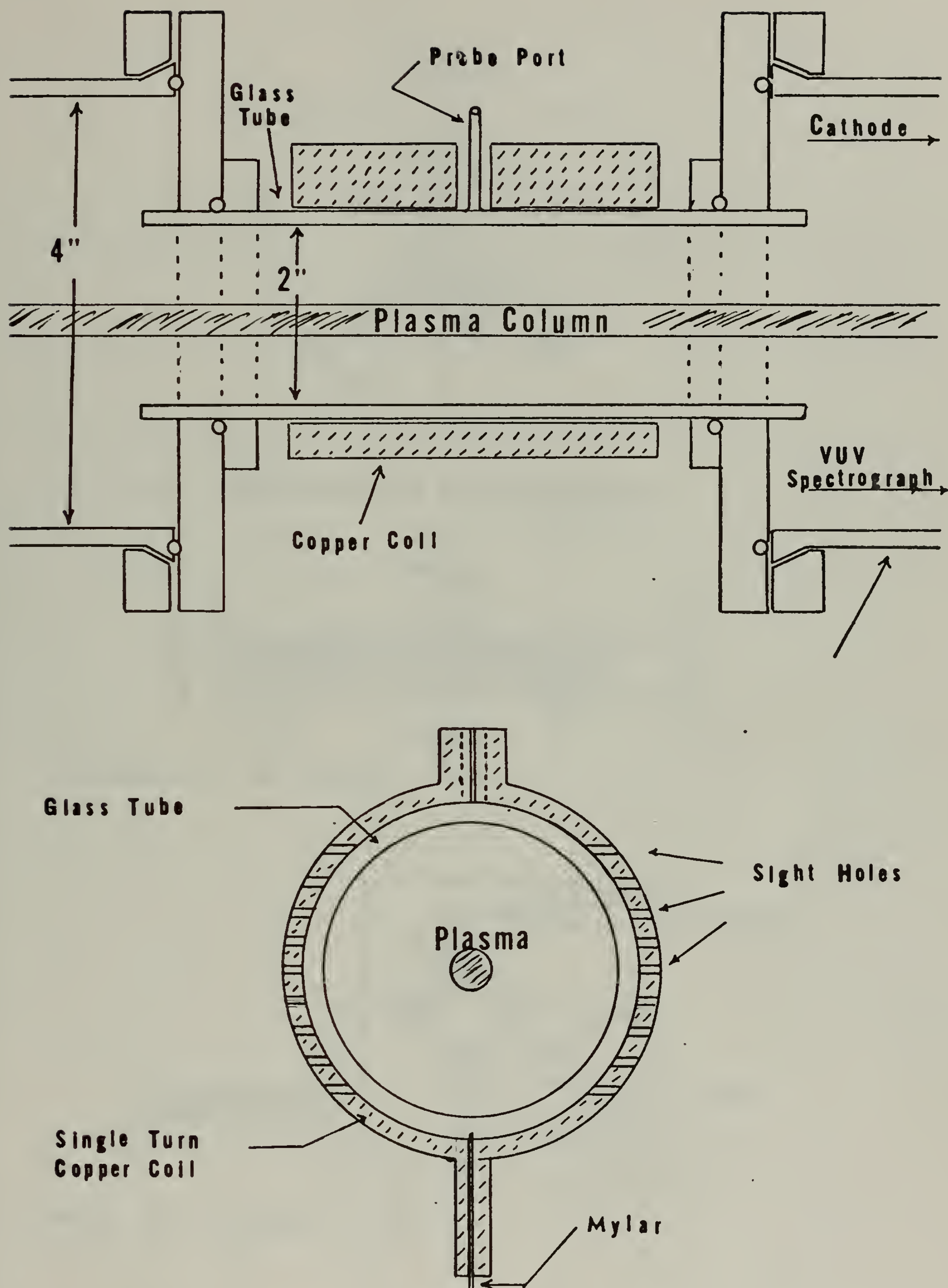
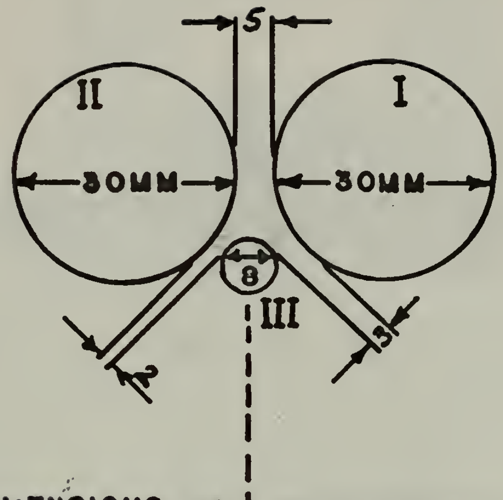
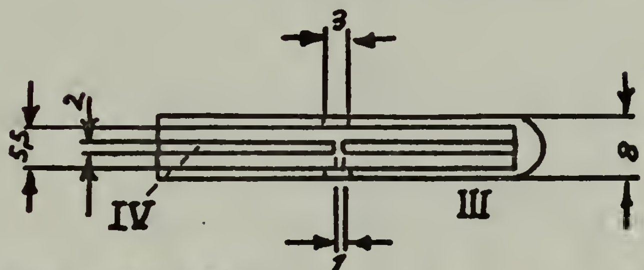


FIG. 5

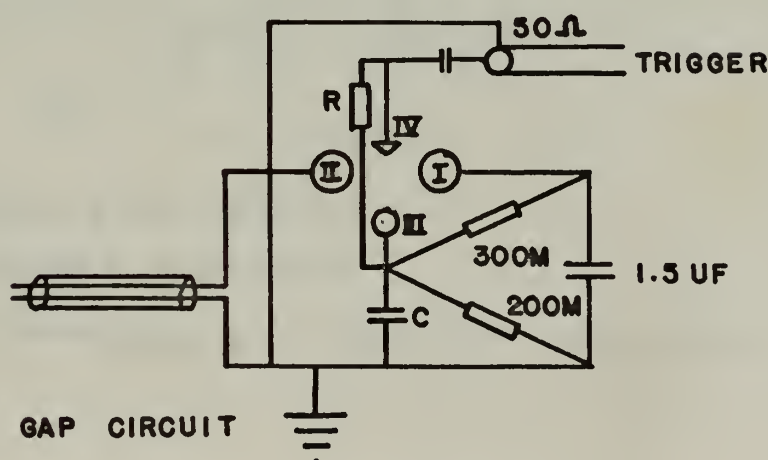
THETA-PINCH COIL



ALL DIMENSIONS IN MILLIMETERS

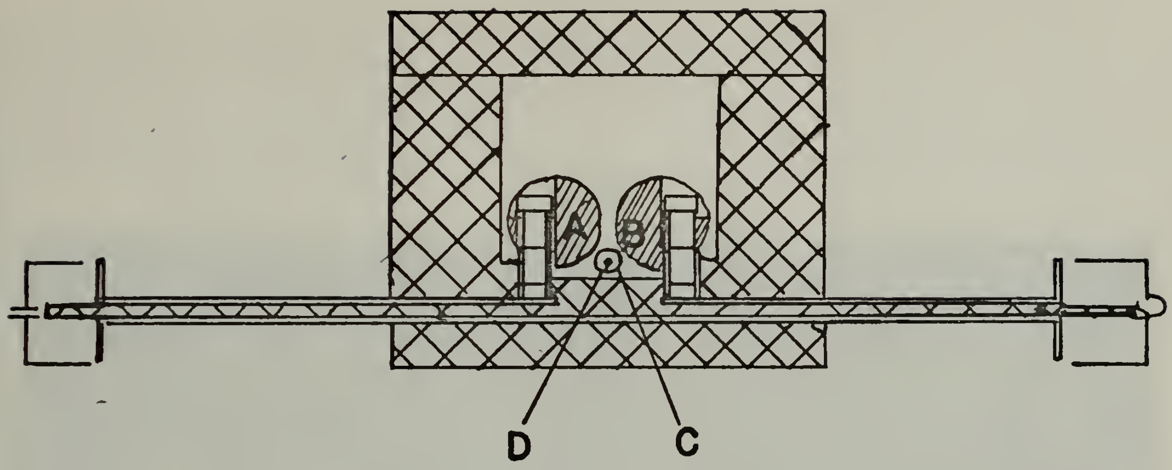


GEOMETRY OF GAPS

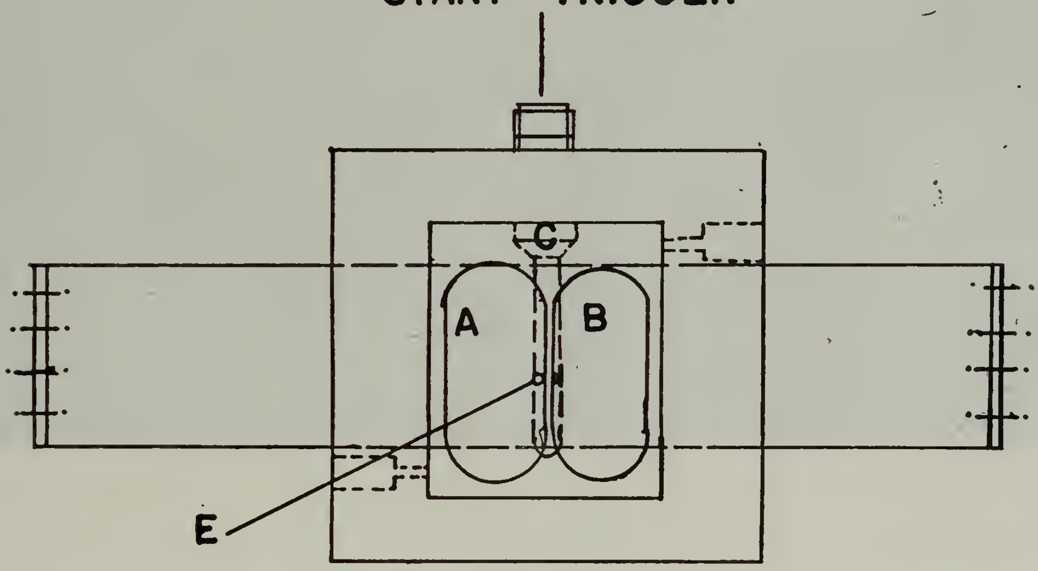


SPARK GAP CIRCUIT

FIGURE 6



START TRIGGER



A,B MAIN ELECTRODES

C TRIGGER ELECTRODE

D IRRADIATING ELECTRODE AND APERTURE E

FIGURE 7 SCHEMATIC OF SPARK GAP

FIGURE 8. SPARK GAP

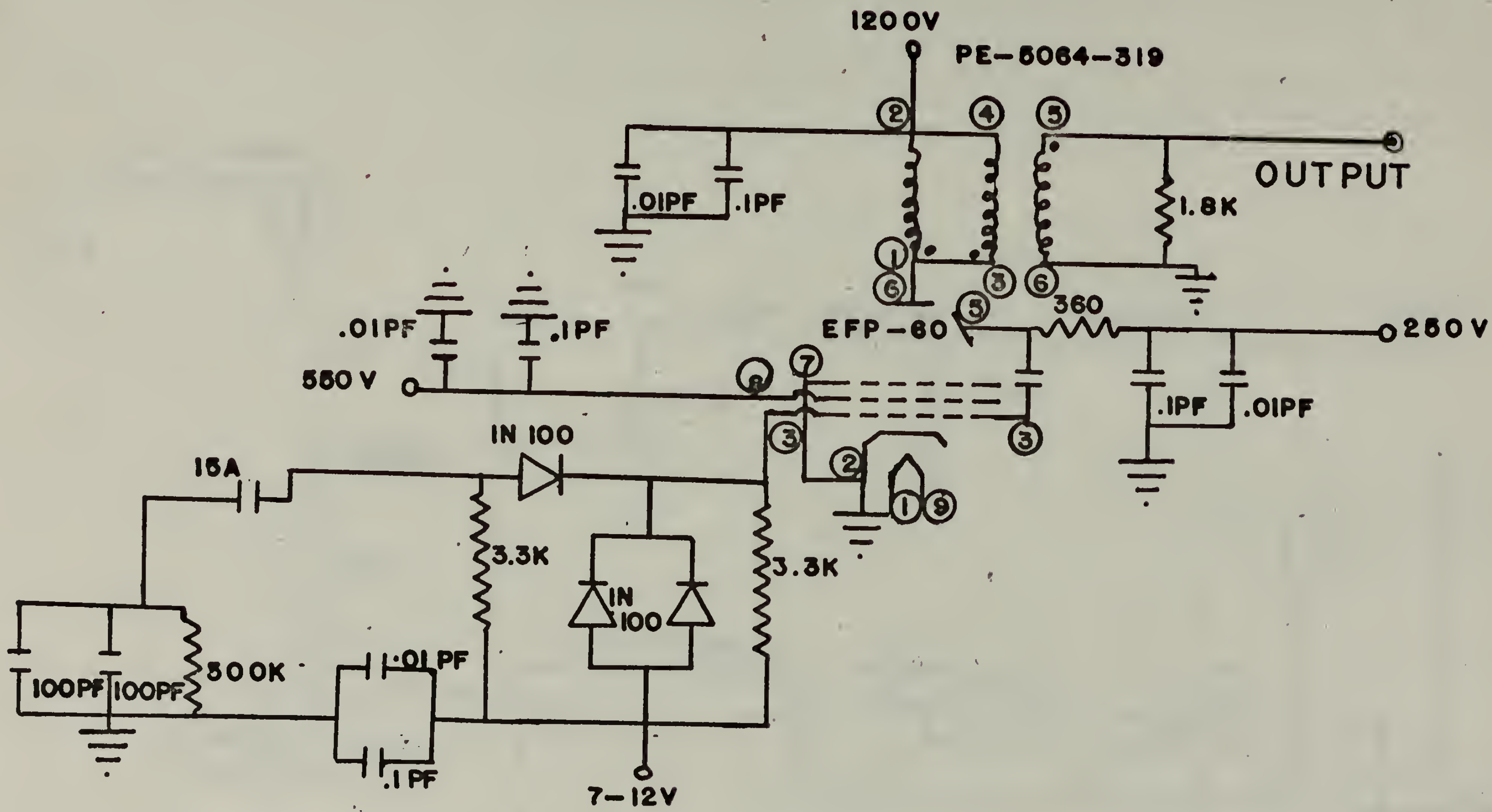


FIGURE 9A TRIGGER GENERATOR

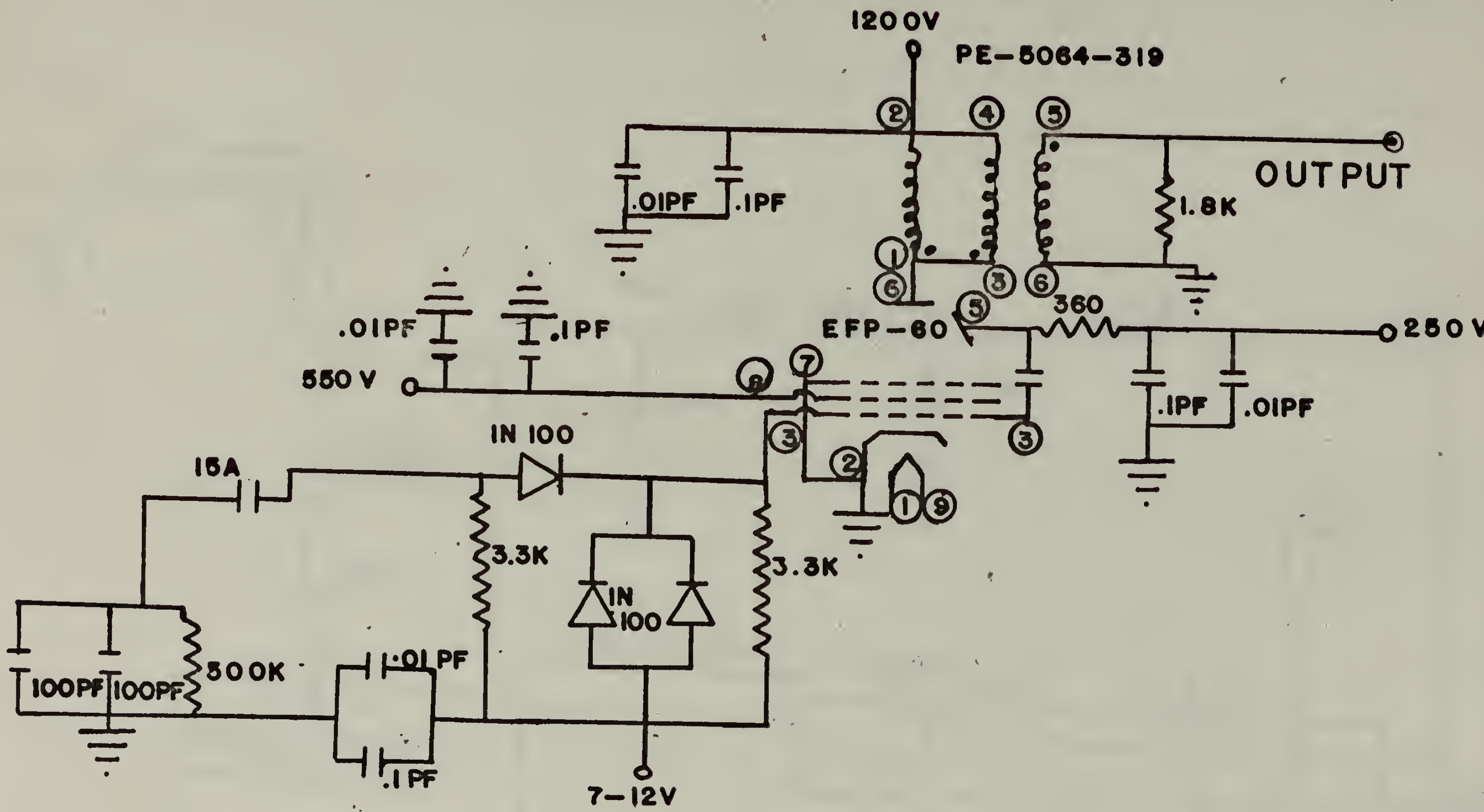


FIGURE 9A TRIGGER GENERATOR

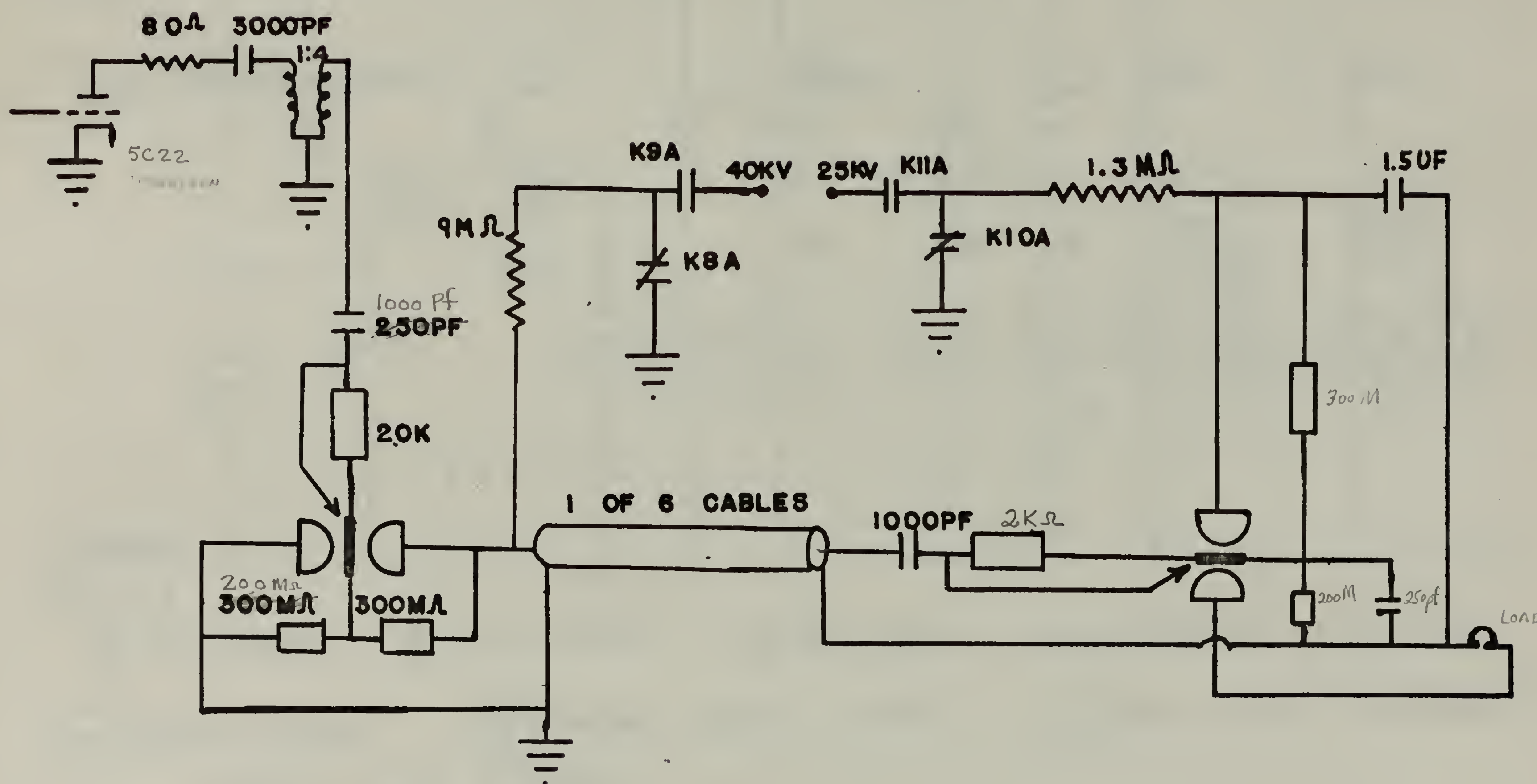


FIGURE 9B. TRIGGER SYSTEM

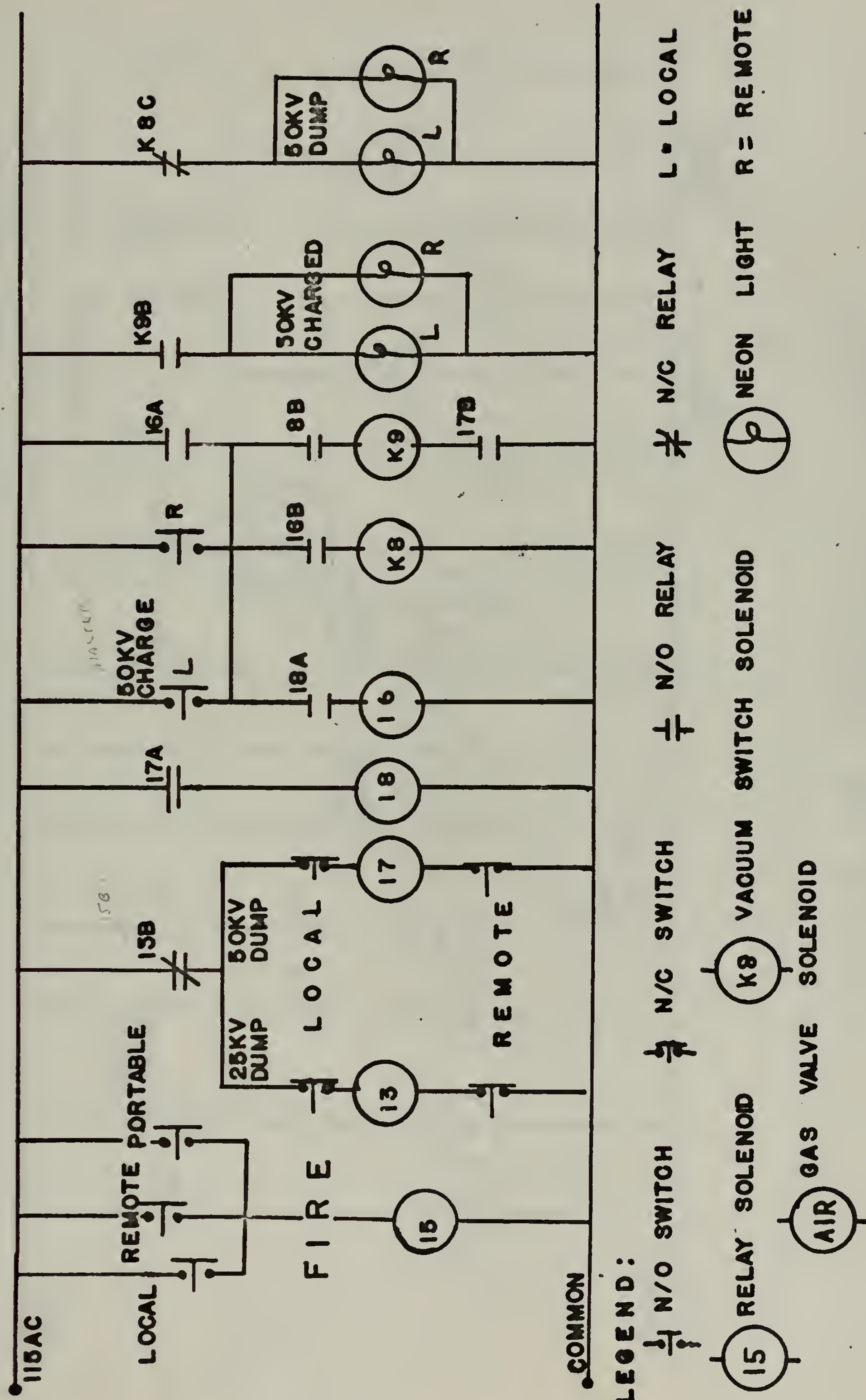


FIGURE 10A CONTROL CIRCUIT

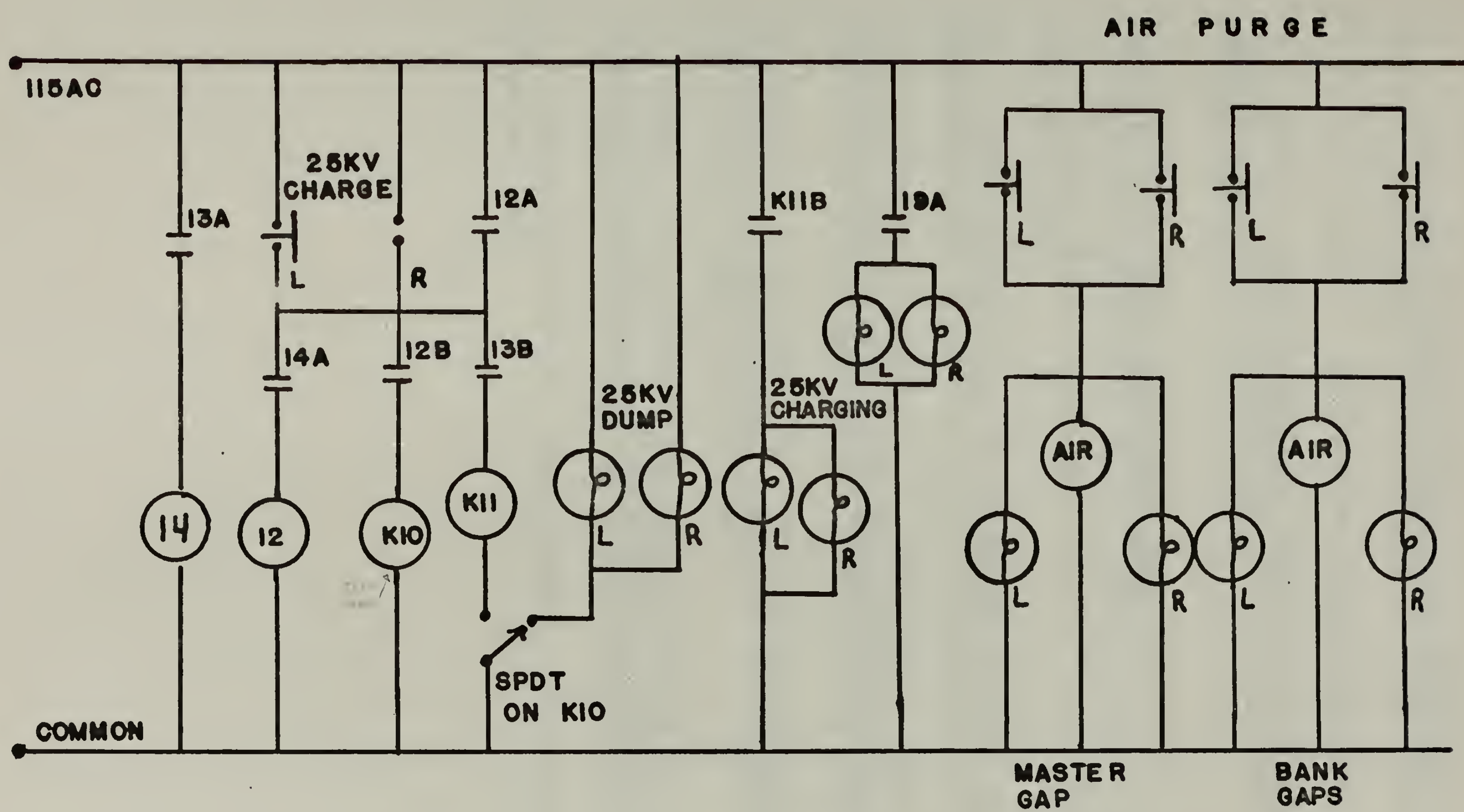


FIGURE 10B CONTROL CIRCUIT

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13. ABSTRACT

A Theta-Pinch device was constructed for the production of shock waves in a nitrogen plasma. The device consisted of six 7 μF capacitors in parallel, and a one turn coil through which the capacitors were discharged. The rise time of the current in the coil is one microsecond, and the stored energy in the capacitors is 13 kJ at 25 kV. The large perturbation of the plasma is expected to produce large amplitude Alfvén waves which would propagate up the plasma column.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Theta Pinch						
Spark Gap Switches						
Pressurized Switches						
Shock Waves						
Fast Bank						

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